# 2. METHODOLOGY OVERVIEW AND REPORT ROADMAP

## 2.1 Introduction

NUREG-0170 [2-1] documents estimates of the radiological consequences and risks associated with the shipment by truck, train, plane, or barge of about 25 different radioactive materials, including power reactor spent fuel. The estimates were calculated using Version 1 of the RADTRAN code [2-2], which was developed for the NRC by Sandia National Laboratories (SNL) specifically to support the conduct of the NUREG-0170 study. When the NRC asked SNL to reexamine the consequences and risks associated with the transport of spent fuel by truck and train, RADTRAN Version 5 [2-3, 2-4], the most recent version of the RADTRAN code, was the computational tool of choice.

The basic methodology employed in the RADTRAN code is widely accepted. Changes to the code are tracked by a software quality assurance plan that is consistent with American National Standards Institute guidelines. Two reviews of RADTRAN Version 4, in which the RADTRAN calculations were benchmarked against hand calculations and other codes, have been published [2-5, 2-6]. Because the models implemented in RADTRAN 5 are almost identical to those implemented in RADTRAN 4, the benchmarking results for RADTRAN 4 also apply to RADTRAN 5.

## 2.2 RADTRAN

The RADTRAN code calculates the radiological consequences and risks associated with the shipment of a specific radioactive material (RAM) in a specific packaging along a specific route. The code estimates consequences and risks (a) for shipments that proceed without incident, that is, for shipments during which no serious accidents occur, and (b) for accident scenarios that might occur during these shipments that could lead to a loss of package shielding or to the release of radioactive material to the environment. Radiation doses caused by shipments that take place without the occurrence of serious accidents are called “incident free.” The doses and risks associated with accident scenarios are referred to as “accident consequences and accident risks, respectively.”

For incident-free shipments, RADTRAN calculates the radiological doses that would be received by workers (e.g., drivers, handlers, inspectors, escorts) and by members of the general public (e.g., persons who live near the RAM transport route and travelers who pass near the RAM transport vehicle while it traverses the transport route). For each accident scenario severe enough to cause a release of radioactive material, RADTRAN estimates (a) the doses that might be received by people who reside downwind of the assumed accident location during the passage of the windborne radioactive plume and as a result of deposition of radioactive materials from that plume onto the ground, (b) the probability of the hypothesized accidental release, and (c) the radiological risks that would be caused by the release (i.e., the product of each radiological consequence and the probability of the release that causes those consequences). RADTRAN can also be used to estimate the radiation doses associated with loss of shielding accidents, that is, with accidents that do not result release of radioactive materials from the package but do cause the radiation shielding of the package to be degraded.

## 2.3 RADTRAN Input

To perform its calculations, RADTRAN requires values for a large number of input parameters. For many of these parameters (e.g., breathing rates, stop times), appropriate values are available in the RADTRAN User's Guide [2-4]. However, the following parameters, all of which strongly influence consequences and risks, have values that vary greatly with route, radioactive material, or packaging characteristics: (a) route lengths; (b) the fractions of those lengths that are urban, suburban, or rural; (c) the population densities and accident rates that characterize those route fractions; (d) the number of people in other vehicles traveling on the route (e) the durations of stops taken while traveling the route; (f) the weather conditions that might prevail at the time of an accident; (g) the surface dose rate of the package; (h) the amount of each radionuclide in the package inventory that might be released to the atmosphere as the result of an accident; (i) the probability of the release; and (j) the time required to conduct an evacuation should a release occur. Because each of these parameters can take on a wide range of values, representative sets of parameter values were developed for each of these parameters. The following sections discuss the more complicated development methods.

### 2.3.1 Route Parameters

In the summer of 1996, when this study was initiated, power reactor spent fuel was stored at 79 locations. Although DOE was required by law [2-7] to begin accepting this spent fuel in early 1998 and overseeing its shipment to temporary and/or permanent storage sites, these shipments have yet to begin because no temporary or permanent storage sites have yet been built. Because the locations of the temporary and permanent storage sites that must eventually be built are not known, this study could not examine a specific set of routes that were certain to be used whenever spent fuel shipments actually take place.

The study could have examined a few specific highway and rail routes that connect some of the sites where spent fuel is presently stored to a few sites that have been mentioned as possible interim or permanent storage site locations. However, because such a minimal set of hypothetical routes could not be shown to be representative (i.e., could not be shown to include routes with characteristics that span the full range of possible routes), a different approach to route construction was adopted.

First, six hypothetical interim storage site locations were selected. Each location selected had been mentioned at some time as a possible site for interim storage of spent fuel and each site was located in a different geographic region of the continental United States, i.e., in the northeast, north-central, northwest, southeast, south-central, and southwest portions of the country. In addition, three possible permanent repository locations (three of the nine sites that entered the Yucca Mountain down-select process [2-8]) were selected, one each in the southeast, south central, and southwest portions of the country. HIGHWAY [2-9] and INTERLINE [2-10] route calculations were then performed that developed route lengths and urban, suburban, and rural route fractions and population densities for 492 routes for each transport mode. Four hundred seventy four of these routes connect the 79 current spent fuel storage locations to each of the 6 hypothetical interim storage site locations. The remaining 18 routes connect these hypothetical interim site locations to the 3 hypothetical permanent storage site locations. These sets of 492 truck or rail routes were then substantially increased in size by adding the results of 249 HIGHWAY and 249 INTERLINE route calculations that had been developed for a prior spent fuel transportation study [2-8]. Thus, route parameter values were available or were developed for a total of 741 different truck and 741 different rail routes.

Next, for both highway and rail routes, distributions of route lengths as well as length fractions and populations densities for the urban, suburban, and rural portions of these routes were constructed using the pooled route data. Then sets of 200 highway and 200 rail routes were generated by sampling these distributions using structured Monte Carlo sampling (Latin Hypercube Sampling [2-11]) methods. Because this sample of routes was constructed by sampling distributions of route parameters based on the characteristics of 741 real truck or 741 real rail routes located throughout the length and breadth of the continental United States, they are believed to constitute a representative set of hypothetical spent fuel shipment routes, even though none of the routes constructed by sampling these route parameter distributions corresponds exactly to any specific real truck or rail route and none has a specific origin or a specific destination.

Because route segment accident rates are not calculated by HIGHWAY or INTERLINE, accident rate distributions had to be developed separately. Heavy truck accident rates on interstate highways and mainline rail accident rates were compiled by Saricks and Kvitek [2-12] for each of the 48 states in the continental United States. For truck accidents (but not train accidents), separate accident rates were reported for accidents that occurred within and outside of incorporated areas. Inspection of state population data for the unincorporated (i.e., rural) and incorporated (i.e., suburban and urban) regions of each state allowed the truck accident rates to be divided into sets of urban, suburban, and rural accident rates. The sets of suburban and rural truck accident rates developed by this procedure were large enough to support the construction of distributions. Because the set of urban accident rates was small, these rates were averaged and the resulting single average urban heavy truck accident rate was applied to all urban route segments.

Because mainline rail accident rates were not developed separately for incorporated and unincorporated areas, a single mainline rail accident rate distribution was constructed using all of the state rail accident rates reported by Saricks and Kvitek [2-12]. Accident rates selected by sampling the resulting distribution were applied to each of the rail route segments in the representative set of 200 rail routes regardless of the population density of the segment. Because mainline rail route traffic densities are determined principally by regional shipping schedules (local shipments are made by truck), they should be largely independent of local wayside population densities. Thus, the use of rail accident rates that do not vary with route segment population density is believed to be reasonable.

### 2.3.2 Weather Parameters

Should a spent fuel shipment be involved in an accident (a collision and/or a fire) that releases radioactive materials to the atmosphere, the radiological consequences of the accident would be determined principally by the amount released, the degree of dilution during downwind transport of the radioactive plume produced by the release, and the size of the exposed population. The degree to which the plume is diluted during downwind transport is determined by the turbulence of the air through which the plume passes, which in turn is determined by the prevailing weather conditions. Because plume dilution is a strong function of atmospheric turbulence, RADTRAN develops accident consequences for six sets of prevailing weather conditions that correspond to the six Pasquill-Gifford atmospheric stability classes [2-13] using national average frequencies of occurrence for each of the classes.

The population exposed to significant levels of radiation is determined principally by the direction in which the wind is blowing at the time of the accident. Because accident locations cannot be predicted and, for most locations, wind speed and direction data (wind roses) would be unavailable, the probability of a specific initial wind direction could not be determined. Therefore, for accident calculations, RADTRAN assumes that all wind directions are equally probable and uses a uniform population density for each route segment selected by sampling the population density distributions developed from the HIGHWAY and INTERLINE results. Although accident consequences would be larger, when the wind is blowing from the accident site toward a small population center then when it is blowing away from that population center, the absence of wind direction data means that this effect could not be modeled. The use of uniform population densities for route segments means that the population densities of small population centers are smeared out, which ensures that the plume always encounters population no matter which way the wind is blowing, even for accidents that occur on lightly populated rural route segments. Thus, the neglect of wind direction, when combined with the use of the uniform segment population densities, is expected to yield a reasonable estimate of mean (expected) accident consequences, even for rural route segments.

## 2.4 Package Inventories and Surface Dose Rates

Although the surface dose rate of a package can be calculated from the package inventory and package design data, this calculation is not performed by the RADTRAN code. Instead surface dose rate and package inventory are both RADTRAN input parameters. Because they are both input parameters, a package inventory may be specified that will not generate the specified package surface dose rate. This study uses package inventories calculated by the ORIGEN code and a distribution of package surface dose rates. To be consistent with regulations, the distribution of package surface dose rates had its maximum value set equal to the regulatory limit for package surface dose rates. Then, in order to assure that accident source terms were conservative, all accident calculations used PWR or BWR ORIGEN [2-14] inventories calculated for high burnup fuel that had cooled for only three years, even though these inventories, if shipped in the generic casks examined by this study, would produce surface dose rates that would exceed the regulatory limit.

## 2.5 Accident Source Terms

Representative accident source terms are developed for discrete sets of truck and train accident conditions. The conditions that define the representative accidents are cask impact speed onto an unyielding surface, impact orientation, and fire duration. For each set of representative accident conditions, the quantities of radionuclides available for release are calculated from the number of rods that fail and the fraction of the rod inventory released upon failure. The amounts released to the interior of the cask are reduced by deposition onto cask internal surfaces. The fraction of the remaining gasborne radionuclides that are transported out of the cask is determined from the fraction of the cask gases that escape from the cask after the cask is pressurized by rod failure and heating of cask gases by accident initiated fires. Deposition times are estimated from cask leak areas which are estimated from the results of finite element cask impact calculations. The probabilities of these representative accident source terms are estimated from the probabilities of the accident scenarios and the probabilities of the accident speeds, cask impact orientations, impact surface hardnesses, occurrence of fires, and fire durations that can be associated with each scenario. These probabilities are called severity fractions because they specify the fraction of all accidents that have characteristics like those that define each representative accident.

### 2.5.1 Source Term Probabilities

The probability of occurrence of a representative accident source term is the product of the chance that an accident of any severity occurs during shipment of the spent fuel and the fraction of all of the possible accidents that yield source terms similar to that source term. Severity fractions were calculated as follows. First, the accident scenarios depicted on the Modal Study [2-15] truck and train accident event trees were determined by inspection to encompass the full spectrum of possible accidents. Next, each scenario probability on these trees was multiplied by the chance that the accident speed falls within one of four speed ranges and/or the chance that the scenario involves a fire that heats the cask to temperatures in one of three temperature ranges. This was done because the conditional scenario probabilities do not reflect the chance that the accident scenario occurs at some particular speed or leads to a fire of some particular severity.

Because Modal Study event trees specify impact surfaces for all collision scenarios, the product of a Modal Study event tree collision scenario conditional probability and the chance that the accident speed falls within one of four speed ranges yields the severity fraction for that collision scenario and speed range. If the collision can also initiate a fire, the product of the scenario probability and the speed range probability is multiplied by the chance that a fire ensues and then by the chance that the fire falls within one of three severity ranges that specify the chance that the fire is an engulfing, optically dense fire that burns hot enough and long enough to cause or increase the release of radioactive materials from the cask to the environment. For non-collision accidents that initiate fires, the chance that a fire of a particular severity ensues is simply the chance that the fire is a severe fire as defined in the preceding sentence. Finally, because accidents of a given severity can be initiated by several different accident scenarios, the probabilities of all scenario, speed, and fire combinations that lead to accidents having similar severities are summed, which gives an estimate of the severity fraction for that set of accidents.

The chance that the accident speed falls within a given speed range is calculated as the difference of the probabilities of the two speeds that define the speed range. These probabilities are read from the accident speed distributions presented in the Modal Study using the impact speeds onto the yielding surface specified for each scenario that are equivalent to one of the four speeds (30, 60, 90, and 120 mph after crushing of the impact limiter, which is equivalent to impact speeds of 42, 67, 95, and 124 mph for an uncrushed impact limiter) examined by the finite element calculations of cask impacts onto unyielding surfaces. The chance that the fire duration is long enough to heat the cask to the temperature where its elastomer seal develops a substantial leak or rods not failed by impact are failed by burst rupture is read from the fire duration distributions presented in the Modal Study.

### 2.5.2 Source Term Magnitudes

The amount of radioactive material that might be released from a failed spent fuel Type B cask as a result of a collision and/or a fire is called the accident source term. The source term can be expressed as the product of four parameters: (1) the inventory of each important radionuclide being transported in the spent fuel cask, (2) the fraction of the fuel rods in the cask failed by the accident, (3) the fraction of the inventory of a single rod that is released from the failed rod to the cask interior, and (4) the fraction of the material that is released from the rods to the cask interior that also is released from the cask interior to the environment. Because cask radionuclide inventories can be precisely calculated by ORIGEN [2-14], development of reasonable estimates of accident source term magnitudes depends on the development of reasonable estimates of rod failure fractions and rod-to-cask and cask-to-environment release fractions for each representative accident examined.

Release of fission products from segments of real and surrogate spent fuel rods has been examined experimentally by Lorenz [2-16, 2-17, 2-18] and Burian [2-19]. A critical review of these experimental results allowed rod-to-cask release fractions to be developed for noble gases, cesium (Cs) compounds, ruthenium (Ru) compounds, and particulates and also for cobalt (Co) in the CRUD [2-20] deposits on fuel rod external surfaces. The values developed reflect blowdown of the rods upon failure, release of Cs and Ru compounds both as vapors and as constituents of particulates, impact fracturing of fuel pellets, formation of particle beds in pellet crack networks and in the pellet-cladding gap, and filtering of particles by these beds during particle transport toward the rod failure location.

Transport of fission products released to the interior of a TN-125 spent fuel cask has been examined by MELCOR [2-21] calculations [2-22]. These calculations show that the efficiency of vapor and particle deposition processes inside of the cask is determined principally by the rate at which the cask depressurizes after pressurization by the failure of spent fuel rods. The calculations also show that depressurization times are determined by the cross-sectional area of the leak path. Because a large leak leads to short depressurization times while a small leak leads to long depressurization times, cask-to-environment release fractions increase as cask leak areas increase. Accordingly, cask-to-environment release fractions can be estimated using the MELCOR results provided the cross-sectional areas of the leaks can be estimated by other methods.

## 2.6 Response of Representative Casks to Accident Conditions

Cask leak areas will depend on cask design and on accident conditions. Specifications (materials of construction and the dimensions of the cask body, lid, and closure) for four generic Type B spent fuel casks (a steel-lead-steel truck cask, a steel-lead-steel rail cask, a steel-DU-steel truck cask, and a monolithic steel rail cask) were developed by review of the characteristics of existing Type B spent fuel cask designs.

The response of these four generic casks to collision and fire accident conditions was then examined by performing finite element calculations and one-dimensional heat transport calculations. The finite element calculations examined cask response to impacts. The heat transport calculations estimated the heating times in engulfing fires that would lead to seal failure due to thermal degradation and rod failure by burst rupture. In addition, the probability of cask puncture during collision accidents was estimated by review of rail tank car accident data.

### 2.6.1 Finite Element Impact Calculations

The response to end, center-of-gravity over corner, and side impacts onto an unyielding surface at 30, 60, 90, and 120 mph of each generic cask, with its impact limiter already fully crushed, was modeled using a version of the PRONTO 3D finite element code [2-23] that runs on a parallel processing computer. PRONTO 3D is a three-dimensional, transient solid-dynamics code that models the large deformations produced in highly nonlinear materials when these materials are subjected to extremely high strain rates. Thus, PRONTO 3D can model the material and geometric non-linearities associated with the large deformations of cask structures that would be produced by high-speed cask impacts. In PRONTO 3D, the modeling of contact between distinct structures allows the various components of the cask to properly transmit loads from one structure to a neighboring structure. This is especially important for modeling the behavior of the cask closure (the cask lid, lid well, and lid bolts). Material failure was not included in any of the models, but accurate depictions, for example, of the deformations and loads on bolts, allows the failure of any single bolt to be predicted although sequential failure of bolts cannot be reliably predicted. The PRONTO code has been validated by comparison of analysis and test results for a wide range of problems, comparison to other finite element analysis results and to theoretical solutions for problems of simple geometry[1]. Many of the validation problems have been developed to exercise the code in regimes typical of impact analyses of spent fuel casks. For example, the Structural Evaluation Test Unit Program [2-24] performed by SNL involved comparison of experimental and analytical results for cask impacts of up to 60 mph. Thus, impacts at speeds as great as 120 mph should be realistically modeled.

Regardless of impact speed and orientation, the strains in truck and rail cask bodies predicted by the PRONTO 3D calculations were always too small to suggest failure of the cask body or of any penetrations that enter the cask through its body. Cask seal leakage and leakage areas were estimated by examining radial and circumferential displacements of the cask closure (i.e., separation of the lid from the lid well). The calculations suggest that truck cask seals are not compromised by impacts at any orientation onto an unyielding surface at 30, 60, and 90 mph and may not leak even after impacts at any orientation at speeds as high as 120 mph. Nevertheless, all 120 mph truck cask impacts were arbitrarily assumed to cause seal leaks with 1 $mm^2$ cross-

1. A Validation and Verification Manual is being prepared, personal communication, M. Blanford, Sandia National Laboratories, 1999.

sectional areas. The results obtained using the finite element models of the two generic rail casks suggest seal leakage may occur for some impact orientations at speeds as low as 60 mph and certainly occurs for some or all impact orientations for impact speeds of 90 and 120 mph.

### 2.6.2 Impacts onto Yielding Surfaces

For any impact speed and orientation, the damage done to the cask by impact onto an unyielding surface would be greater than the damage done by impact onto a yielding surface (hard and soft rock, hard and soft soils, concrete, water, drainage ditches, and road and rail beds). Because unyielding surfaces rarely occur in the real world, the impact speeds onto real world yielding surfaces, that are equivalent (cause the same cask damage) to each impact speed used for the unyielding surface, finite element calculations (30, 60, 90, and 120 mph) had to be calculated. This was done as follows.

First, for each unyielding surface impact calculation, a cask velocity time-history was calculated from the kinetic energy time-history. Next, the displacement of the center of gravity of the cask and the cask's rigid body acceleration were calculated respectively by numerical integration and differentiation of the velocity time-history. A force time-history was now calculated assuming that the contact force between the cask and the unyielding surface is equal to the rigid-body acceleration times the mass of the cask. Combination of the force time-history and the displacement time-history for any cask impact then produced a force-deflection curve for that unyielding surface impact calculation.

Impact of a cask onto a real yielding surface will produce damage equivalent to that observed for impact onto an unyielding surface only if the peak contact force for cask impact onto the yielding surface equals the peak contact force on the force-deflection curve developed for impact onto an unyielding surface. The energy absorbed by the yielding surface during each impact that developed a peak-contact force of this magnitude was now added to the initial kinetic energy of the unyielding surface impact. The velocity that corresponds to this total kinetic energy is the velocity for impact onto the yielding surface that is equivalent to the unyielding surface impact velocity (i.e., the velocity that would produce the same cask damage as that predicted for the unyielding surface impact at the specified impact velocity and orientation).

## 2.7 Rod Failure Fractions

The fraction of the fuel rods in each generic cask that are failed by end, corner, and side impacts of the cask at 30, 60, 90, or 120 mph onto an unyielding surface after crushing of the cask impact limiter was estimated from the peak rigid-body accelerations predicted by finite element analysis at each speed and impact orientation. First, the rod cladding strains calculated by Sanders, et al. [2-25] for 100 G side impacts onto an unyielding surface by a spent fuel cask carrying a typical pressurized water reactor or a typical boiling water reactor assembly were scaled to match the peak rigid-body accelerations predicted by the finite element impact analyses for each generic cask at each impact speed and impact orientation. Then, the fraction of rods that fail was estimated by comparing the scaled cladding strains to the 4 percent strain level predicted by Sanders, et al. to lead to cladding failure in typical spent fuel rods. Because rod strains generated by side impacts were used to evaluate all of the finite element results, the fraction of rods estimated to be failed by end and corner impacts is conservative as rod damage for these impacts is expected to be less than that produced by side impacts with the same cask acceleration.

## 2.8 Thermal Calculations

Rod failure by burst rupture and times to failure for fire accident scenarios were estimated using the PATRAN/PThermal [2-26] analysis code, which is available commercially [2-27]. PATRAN/PThermal models all of the heat transfer processes (i.e., conduction, convection, and thermal radiation) that determine the heating rates of structures. Thus, the code can be used to perform one-, two-, and three-dimensional simulations of the effects of ambient conditions and fire conditions on the temperatures of spent fuel packages. PATRAN/Pthermal, formerly called Q/TRAN, has been validated by comparison of its results to analytic solutions and to predictions made by other thermal transport codes widely used in the transportation industry [2-28, 2-29].

PATRAN/PThermal results were developed for each of the four generic spent fuel casks examined by the finite element calculations. For these thermal calculations, the cask's neutron shield material compartment was assumed to be empty. The compartment was modeled as empty because, after the shield material in the compartment drains or burns away, as would be expected to happen during a severe fire accident, radiative and convective heat transport to the cask body through the empty compartment will significantly influence the rate of temperature rise of the cask body.

For each generic cask, the PATRAN/PThermal calculations determined the duration of a fully engulfing, optically dense, hydrocarbon fuel fire that would heat the cask to the temperature at which spent fuel rods would fail by burst rupture. The probability of fires of this duration was then used as an input to the calculation of accident severity fractions. During the calculation of release fractions, it was assumed that any fire that raised cask internal temperatures to rod burst rupture temperatures would also cause the failure of all unfailed rods in the cask. To assure that the calculated fire durations were conservative (shorter than the times actually required to reach seal leakage or rod burst rupture temperature), all of these calculations used a heat flux to the inner surface of the shell of the cask that was appropriate for high burnup fuel that had cooled for only three years.

The temperatures that cause seal leakage and the cross-sectional leak areas produced by thermal degradation of cask seals are estimated from literature data as follows. About 70 percent of the mass of elastomeric seal materials, including Viton, was lost during thermogravimetric analysis (TGA) experiments [2-30] during which these seal materials were heated to 500ºC at heating rates like those predicted here for heating of the four generic casks in engulfing optically dense hydrocarbon fires. Thus, heating a spent fuel cask to 500ºC is assumed to cause the cask's elastomeric seals to fail completely due to extensive thermal degradation. If a cask containment is lost due to thermal degradation of its elastomeric seal, the cask depressurization time will be determined by the leak rate of cask gases through the metal-to-metal gap between the cask lid and the lid well. Because bolt softening during cask heating by a hot, long-duration fire is expected to essentially eliminate the compression between the lid and the lid well around the entire circumference of the cask closure, the resulting leak area is assumed to equal the product of the surface roughness of the closure and the closure circumference.

## 2.9 RADTRAN Calculations

Seven sets of RADTRAN calculations were performed. Most of the calculations were performed with RADTRAN Version 5. A few calculations in the fifth set of calculations were performed with RADTRAN Version 1.

Sets one and two used the 200 representative truck and rail routes that were developed by Latin Hypercube Sampling of the route parameter distributions. The results of these calculations depict the possible range of spent fuel transportation consequences and risks.

Sets three and four developed results for ten specific shipment routes, five truck and five rail routes. Two of the ten routes were the national average spent fuel shipment truck and train routes constructed for the NUREG-0170 study [2-1]. The other eight routes were the truck and train routes that connect reactor sites to hypothetical interim storage locations. This set of calculations was performed in order to show that the results obtained for real routes fall within the envelope of results developed using the 200 representative routes constructed by sampling route parameter distributions.

Set five compared the consequences and risks predicted for spent fuel shipments by RADTRAN Version 1, the version of RADTRAN used during the NUREG-0170 study [2-1], to those predicted for this study using RADTRAN Version 5. These calculations depict the influence of cask inventory, spent fuel release fractions, and exposure pathway models on spent fuel transportation consequences and risks.

Sets six and seven compared the consequences and risks obtained using the cask inventory and release assumptions developed for the NUREG-0170 study [2-1], the Modal Study [2-15], and this study. These calculations illustrate the influence of the chemical and physical phenomena modeled on source term magnitudes and thus on consequences and risks.

## 2.10 Report Roadmap

The methods briefly outlined in this section are fully described in the following sections of this report. RADTRAN input parameter values are discussed in Section 3. Section 3.1 describes the selection of the RADTRAN parameters for which distributions are developed, Section 3.2 specifies values for the RADTRAN parameters for which central estimate values are used and provides a brief description of the basis for each value, and Section 3.3 describes how the parameter distributions were constructed.

The review of spent fuel transportation cask properties and the development of specifications for the four generic casks examined by this study is described in Section 4. Section 5 presents the results of the finite element unyielding surface impact calculations performed using the finite element model of each generic cask and the extrapolation of these results to yielding surfaces. The thermal analyses of the four generic casks are presented in Section 6.

The development of accident source terms is described in Section 7. Section 7.1 reexamines the truck and train accident scenarios depicted by the accident event trees constructed for the Modal Study [2-30]. Severity fraction and release fraction expressions are developed in Section 7.2.

Sections 7.3 and 7.4 respectively develop values for the parameters in these severity and release fraction expressions. Section 7.5 then presents the source terms (sets of release fractions and the severity fraction to which they correspond) calculated using these parameter values.

The RADTRAN calculations performed for this study and the results (spent fuel transportation incident free and accident consequences and risks) of these calculations are described and discussed in Section 8. Section 8.1 presents the results of the calculations that used the route samples of size 200 that were constructed by Latin Hypercube Sampling of route parameter distributions; Section 8.2 presents the results obtained for the ten specific routes for which calculations were performed; Section 8.3 compares the estimates of consequences and risks obtained using the source terms developed for the NUREG-0170 study, the Modal Study, and this study; and Section 8.4 examines the effects of changing the inventory, release fraction, and pathways modeled during the NUREG-0170 study to those used during this study.

Finally, Section 9 briefly discusses the results of the study and presents the study's conclusions.

## 2.11 References

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